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A NATURE-INSPIRED ALGORITHM TUNED MAXIMUM POWER POINT CONTROLLER FOR THE PHOTOVOLTAIC SYSTEM

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ABSTRACT

Nowadays, solar photovoltaic (PV) systems are promising renewable power alternatives in reality. Harvesting the utmost electricity from a PV system under changeable environmental conditions is a complex challenge. This work demonstrates how to get additional energy from a solar power system by combining it with a step-up converter. As a result, academics are heavily researching strategies for increasing the efficiency of solar power facilities. The standard techniques of maximum power point tracking (MPPT) control are quick and straightforward to apply; however, the conventional MPPT techniques have some limitations, such as start-up stability and the inability to monitor the utmost power under fast-fluctuating solar radiations. Numerous bio-inspired MPPT techniques have been reported in the works of literature. Using a nature-inspired algorithm called hurricane algorithm (HA), a strategy is suggested to optimize the MPPT controller. This work offers an HA-based MPPT approach to attain the optimum duty cycle to regulate a step-up converter. Using the MATLAB Simulink platform, the efficacy of the presented system was validated and compared to the traditional perturb and observe (P&O), and the incremental conductance (IC) based MPPT algorithms under start-up and transient conditions. Finally, the results of the simulation study were shown through comparative studies. The proposed HA-based MPPT approach delivers excellent dynamic and steady-state performance in contrast to the IC and P&O-based power tracking techniques, validated on the basis of settling time, rising time, and maximum percentage overshoot. The simulation results also show that the proposed HA-based MPPT algorithm outperforms traditional solutions in terms of efficiency and control.

Keywords: DC-DC boost converter; maximum power point tracking; nature-inspired algorithm; photovoltaic system

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1. INTRODUCTION

The socio-economic impact of supplying power from renewable power sources rather than conventional generations methods is now considered for the local economy [1]. Differences in employment, earnings, and gross productivity are influenced by socio-economic factors, either directly or indirectly. The construction of a modern power system has substantial socio-economic consequences, such as raised local and territorial employment, output, and gains in the country's economy. Electricity may be generated with near-zero air pollutants and greenhouse gas emissions utilizing renewable energy sources and local resources. Furthermore, the expansion of renewable energy sources is linked to environmental, health, and environmental protection advantages, among other things.

Photovoltaic (PV) energy ranks first on the list of green energy sources because it is more widely dispersed in nature than any other renewable energy source [2]. Currently, PV sources are widely employed for distant-independent and grid-connected renewable energy systems [3]. PV energy is infinite and plentiful in nature. It is pure and green energy that emits no air pollutants and greenhouse gas emissions, thus minimizing its influence on the environment [3]. Nevertheless, the problem of solar PV power production depends on environmental conditions. The output power of the PV module is a mathematical formulation of the diode junction temperature and light strength that fluctuates regularly over the period. PV devices are well recognized for their positive environmental impacts, including minimal noise or chemical pollutants during operation. The amount of energy produced by a PV device is determined by sunlight insolation and temperature.

The predicted cumulative installed capacity figure of the PV system is more significant than expected by 2020 [4]. The biggest disadvantage of PV systems is that the quantity of energy generated is continually changing due to changing climatic circumstances. On a cloudy day, there was a higher variance in solar insolation. As a result, unique methods for extracting maximum power from solar modules under every climatic situation, known as maximum power point tracking (MPPT), are required. The PV system's power-voltage (P-V) curve has numerous maximum points under these circumstances, making estimating the maximum power operating point (MPOP) challenging. In order to simulate an efficient PV system, proper MPOP regulation is required. The MPPT techniques are implemented in power converters that transform the energy from the PV array to be compatible with the loads. As a result, MPPT becomes even more critical for PV systems to operate at their best. MPPT approaches are based on a software program that looks for MPOP based on evaluated solar module characteristics (voltage, current, and power) [5].

Shading is discussed in Xiao et al., and it plays an essential role in restricting the solar power output [6]. Under varying shading conditions, the inclusion of bypass diode in the series-parallel combination creates several maxima in P-V properties of the series-parallel combination. Several MPPT approaches were proposed over the last two decades. The incremental conductance (IC), perturb & observe (P&O), and Hill-climbing (HC) procedures are examples of traditional methodologies. The P&O and IC algorithms are the most widely utilized MPPT techniques [7]. The P&O and IC processes with fixed iteration are simple and effective.

Nonetheless, delayed convergences, oscillations in output power across the MPOP, and malfunctioning when atmospheric conditions change characterize these methods. Although utilizing a tiny disturbance step size reduces oscillation, the MPOP tracking rate remains poor. The P&O MPPT algorithm's shortcomings include that the operating point oscillates about the MPOP, resulting in the loss of some available energy even in a stable condition [7]. Several suggestions for improving the P&O technique have been made to reduce the total count of oscillations close to the MPOP at steady-state conditions, but this can slow down the technique's response to changes in solar insolation and temperature, as well as reduce the MPPT technique's efficiency on cloudy days. The IC MPPT approach has more hardware and simulation complexities than the P&O MPPT technique, and it also takes longer to execute and slows down the sample rates of PV current and voltage measurements. Both IC and P&O may be incorrectly described during specific periods of variable solar insolation and temperature; both IC and P&O approaches may be incorrectly described since the operating point may wander outside the MPOP instead of keeping closer to it. P&O and IC are two current MPPT algorithms that presume an estimated maximum power point on the PV curve and cannot ensure convergence to true MPOPs. Because they can't tell the difference between a true global high and a local peak, these tactics often become trapped at a local peak. The method's limitation of limiting to a single local maximum point (LMP) may be helpful only for uniform radiation situations and not for partly darkened settings.

Renaudineau et al. employed the particle swarm optimization (PSO) approach extensively in multiple global maximum power point tracking (GMPPT) procedures [8]. Fuzzy and neural network models are used in a variety of PV applications to remove non-linearity. Solving the global MPPT issue, on the other hand, is not a simple process. A multi-start approach is often utilized when deterministic local search techniques are used for this purpose, which does not guarantee a global optimum at the end. Stochastic search techniques are more promising for these objectives since they are significantly more efficient at searching the entire search space and then localizing it in the most exciting sections. Due to its metaheuristic qualities, swarm optimization methods, a version of the stochastic search technique, are ideally suited for handling such issues.

Over the last three decades, several MPPT techniques for PV systems have been published in the literature. In [9], [10], the authors suggested improving the GMPPT by parameter adjustment of PSO algorithm, reducing the iteration count, computing duration, and start-up oscillation. There are 19 distinct methodologies used, including some tweaks to established methods. Monitoring the MPOP of a PV module has been successfully researched by several scientists and programmers. The PSO was used by Li et al. to calculate each module voltage in a modular PV system with centrally applied MPPT control [11], where the particle swarm based algorithms overcome most of the shortcomings of Fibonacci search and HC under various environmental situations [12]. The complexity, precision, speed, MPOP fluctuations, and sensors needed to switch on the equipment change across these tactics. In the literature, there are many approaches for optimizing the transmission of PV energy to varied loads. Others have modified the array setup (module serial-parallel switching) to match the MPOP to fit the loads, while others depend on the selection of PV module characteristics to handle these loads. In [13], the author used a hybridization of PSO and P&O approaches to track the global maximum point (GMP). The P&O algorithm is used initially to find the closest local maximum power point, and then PSO algorithm is used to decrease the search space and convergence time in tracking GMP. When compared to PSO, the genetic algorithm (GA) is determined to have high exploration capabilities, despite the fact that it sometimes leads to early convergence. GA's multiple operators, including selection, crossover, and mutation, allow it to effectively adjust the exploration and exploitation. In addition to hybridizing algorithms, the adjustment of adaptive parameters has shown assuring outcomes for the PSO and GA. In GA algorithm, adaptive control is used for mutation and crossover rates, whereas in PSO algorithm, adaptive

adjustment is applied to the inertia weight, resulting in improved outcomes for various optimization issues [14]. To obtain excellent results in multimodal optimization issues, some studies focus on combining adaptive adjustment on inertia weight in PSO algorithm with adaptive adjustment on mutation and crossover rates in the GA algorithm.

The grey wolf optimizer (GWO), firefly algorithm (FA), and bat algorithm (BA) are some of the most recent optimization approaches based on swarm intelligence that have been reported in the literature [15]. BA imitates the navigation of bats, whereas DEL imitates the discovery of prey by dolphins. FA simulates the mating behavior of fireflies. The grey hunting style of grey wolves was modeled in the GWO. The Grey hunting style of grey wolves is modeled after GWO. Cuckoo Search (CS) is a new algorithm based on the reproduction mechanism of cuckoos. In the literature, various alternative algorithms have been developed with various sources of inspiration. The flower pollination algorithm (FPA) is inspired by the reproduction and survival of flowers via pollination. The state of matter search (SMS) is a problem-solving method established on the notion of different phases of matter.

For this reason, the optimization method used should be capable of excellent exploitation and exploration with a short convergence period. The hurricane algorithm (HA) is a nature-inspired multi-agent global optimization algorithm based on metaheuristics and replicates the behaviour of wind parcels in a hurricane [16]. Because of its great capacity for exploitation and exploration, local minimum avoidance, and remarkable convergence, HA-based MPPT is suggested in this study. To achieve the destination, each wind parcel will alter its location in a social network, and it will go through two phases: exploration and exploitation.

The proposed approach is a fast MPPT algorithm that can be used to (i) find the GMPP and improve the efficiency of the PV system, (ii) effectively track the maximum power point under both start-up and dynamic environments, and (iii) shortening convergence period. The remainder of this paper is summarized as follows. Section 2 shows the single diode model and maximum power operating point in I-V property of a real PV cell. The basic ideas and implementation of the HA-based MPPT technique are explained in Section 3. Section 4 presents the results and comments. Section 5 presents the conclusion of this study.

2. SINGLE DIODE MODEL

Fig. 1 shows a schematic of a PV cell with one diode. The basic equation of an ideal PV cell, which depicts the current-voltage property of a PV cell and can be formulated as,

$$I = I_{pv}^{cell} - \underbrace{I_0^{cell}\left[exp\left(\frac{qV}{\alpha k T_{jun}}\right) - 1\right]}_{I_d} \tag{1}$$

The I-V curve of a perfect PV cell is shown in Fig. 2. The I-V characteristic of a real PV cell is depicted in Fig. 3. The single diode model achieves an excellent blend of simplicity and accuracy. This model is straightforward, and numerous researchers in the past have utilized it, generally with a smaller version that nevertheless includes a parallel diode current source.

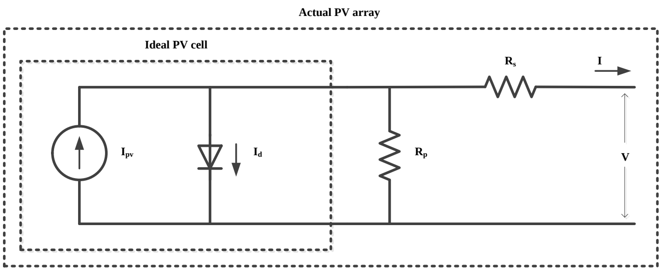

Figure 1 Single diode model

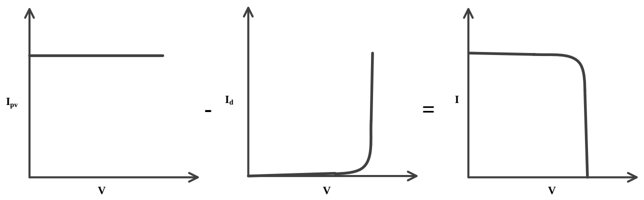

Figure 2 Ideal PV cell - I-V curve

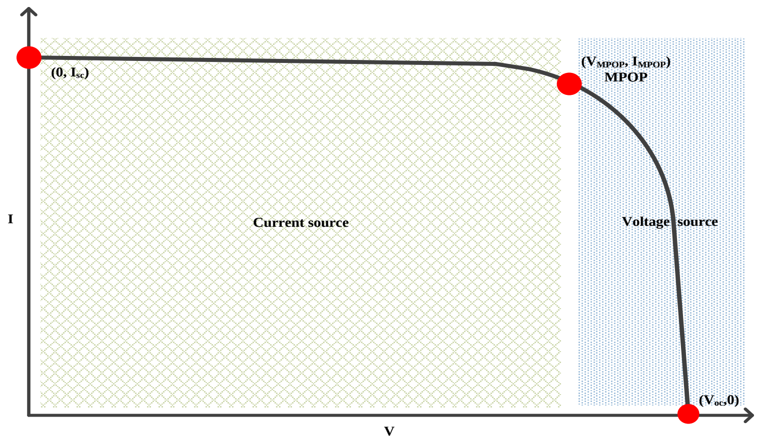

Figure 3 I-V characteristic

3. HURRICANE ALGORITHM

The concept behind the presented HA is based on hurricane observations and how wind packets flow across the environment. Many equations represented this phenomenon. The first provides an overview of the wind environment. The concept was initially applied to storms by Depperman, and it was dubbed Rankine combined or modified Rankine vortex [16].

Consider a system with N parcels. The position of the i^{th} parcel is $X_i = (x^1_i,\dots,x^d_i,\dots,x^n_i)$ for i 1,2,3,...,N. x^d_i presents the position of i^{th} parcel in the d^{th} dimension, and n the search space dimension [16]. Wind parcels are divided into j (=n-1) groups, whereas each parcel Xi ϵ Gk (k = i mod (n-1)).

Consider the parcel Xi ϵ Gk denoted (X^k_i), the components x^j_i (j = 1, 2, 3, ..., n) are calculated, starting from the eye position, as follows:

$$x_i^j = \begin{cases} r_i(t).cos(\varphi^i_{initial} + \varphi_i(t)) + e_j & if \quad j = k \\ r_i(t).sin(\varphi^i_{initial} + \varphi_i(t)) + e_j & if \quad j = k+1 \\ e_j & otherwise \end{cases} \qquad (2)$$

$$r_i(t) = R_0.exp(rand \cdot \varphi_i(t))$$

where r_i and φ_i are radial and angular coordinate in polar coordinates, respectively. R_0 is the eye radius that is a user parameter in the interval [0,+∞]. The values $\varphi^i_{initial}$ (i =1, 2, 3, …, N) is produced arbitrarily in the period [0, 2π]. At t = 0, $\varphi_i(0) = 0$ and $r_i(0) = R_0$. This means that at t = 0, R_0 and $\varphi^i_{initial}$ are the initial polar coordinates, ej presents the j^{th} component of the eye, and rand is a random number in the interval [0,1]. In other words, each parcel X^k_i from the group Gk moves along a spiral path in the plane formed by the two dimensions k and k+1. Parcels need velocity to start and keep moving. Hence, the velocity of a parcel X^k_i is considered as a rate of change of angular displacement (angular velocity) added to its angular coordinate φ_i:

$$\begin{cases} \varphi_i(t+1)) = \varphi_i(t) + \omega; \quad if \quad r_i \le R_{max} \\ \varphi_i(t+1)) = \varphi_i(t) + \omega \cdot \left(\dfrac{R_{max}}{r} \right)^{rand}; \quad if \quad r_i > R_{max} \end{cases} \tag{3}$$

where ω is the angular velocity defined by the user within the interval [0, 2π]. R_{max} is the radius of the maximum wind speed. This parameter is defined in the interval [0,+∞]. Under the constraint $R_0 < R_{max}$. rand is a uniform random variable in the interval [0, 1]. Each time parcel Xi k changes position. If $P_i < P_{eye}$, the eye moves to the parcel position in order to keep the lower pressure at the eye. P_i and P_{eye} are defined as follows,

$$P_i = fit_i = f\left(x_i^1, ..., x_i^d, ..., x_i^n\right)$$

$$P_{eye} = \begin{cases} \underset{i \in \{1,...,N\}}{arg\,min} \quad fit_i(t); \quad minimization \\ -\underset{i \in \{1,...,N\}}{arg\,max} \quad fit_i(t); \quad maximization \end{cases} \tag{4}$$

where $fit_i(t)$ represents the fitness value of the parcel X_i^k at the time t.

3.1. Implementation of HA

Step 1: Read HA parameters such as it_{Max} - maximum number of iterations,

Step 2: Set the initial iteration number as it = 1.

Step 3: Arbitrarily assign initial working solutions for 'm' parcel in vector form as $x_i=[x_{i1}\ x_{i2}]$, i = 1 to m;

Step 4: For each parcel i, calculate the fitness function of the test system. Repeat this step for all other parcels.

Step 5: Find out the i^{th} parcel's pressure.

Step 6: Move the wind parcel to the next location.

Step 7: After a preset number of iterations (it_{Max}), the algorithm delivers the optimal solution, which is the eye position.

4. RESULTS AND DISCUSSION

The switching frequency f_s of the step-up boost converter is set at 5 kHz in this research. The converter parameter determines the PV producing system's static behavior. As a result, the identical DC-DC boost converter design and related characteristics are used to compare the proposed HA-based MPPT controller with the traditional P&O and IC MPPT controllers. Numerical simulations in the MATLAB Simulink environment are used to examine and validate the proposed HA-based MPPT algorithm, P&O, and IC algorithms.

4.1. Case Studies

Table 1 shows the steady-state response characteristics of PV terminal voltage V_{PV} and load voltage V_{Load} after the simulation is completed for t_{sim} = 1.5 s. Table 1 also shows the rising time, settling time, and overshoot of the load and PV voltages. Table 2 compares the average power P_{PVavg} extracted from the PV panel with the average power $P_{Loadavg}$ used by the resistive load for all of the MPPT strategies mentioned.

The steady-state response of PV array output power, PV terminal voltage, and current as a function of solar insolation and temperature is shown in Fig. 4. Both solar insolation and temperature are held constant in this research. With a t_{settle} of 0.57 s, the IC MPPT approach takes substantially longer to settle than the PV voltage waveform in Fig. 4. Similarly, the P&O

MPPT technique takes 0.30 s to settle faster than the IC approach. Meanwhile, the given HA-based MPPT algorithm settles swiftly, as shown in Table 1, with a t_{settle} of 0.30 s. Under constant solar insolation and temperature, the presented HA-based MPPT algorithm settles the PV voltage significantly quicker than the classic MPPT techniques namely P&O and IC, as shown in Fig. 4. Nevertheless, the P&O and IC MPPT methods have an overshoot of 0.56 percent and 8.43 percent, respectively. The presented HA-based MPPT approach has a meager 0.30 percent.

Fig. 5 shows a resistive load's power, voltage, and current response to constant solar radiation and temperature. The voltage waveform across the resistive load in Fig. 5 shows that the IC MPPT method takes longer to settle, with a t_{settle} of 0.62 s; the P&O MPPT approach takes slightly longer to settle, at 0.31 s; and the presented HA algorithm based MPPT controller settles rapidly, at 0.30 s. For both P&O and IC MPPT procedures, the voltage across the resistive load has an overshoot of 0.03 percent. In comparison, the load voltage for the proposed HA-based MPPT methodology has a minimum overshoot of 0.01 percent.

Table 1. PV Voltage and Load Voltage Response

Time (s)	Algorithm	Voltage	Rise time (s)	Settling time (s)	Overshoot (%)
$0 < t_{sim} < 1.5$	P&O	V_{PV}	0.17	0.30	0.56
	IC		0.44	0.57	8.43
	Proposed		0.17	0.30	0.30
	P&O	V_{Load}	0.18	0.31	0.03
	IC		0.46	0.62	0.03
	Proposed		0.18	0.30	0.01

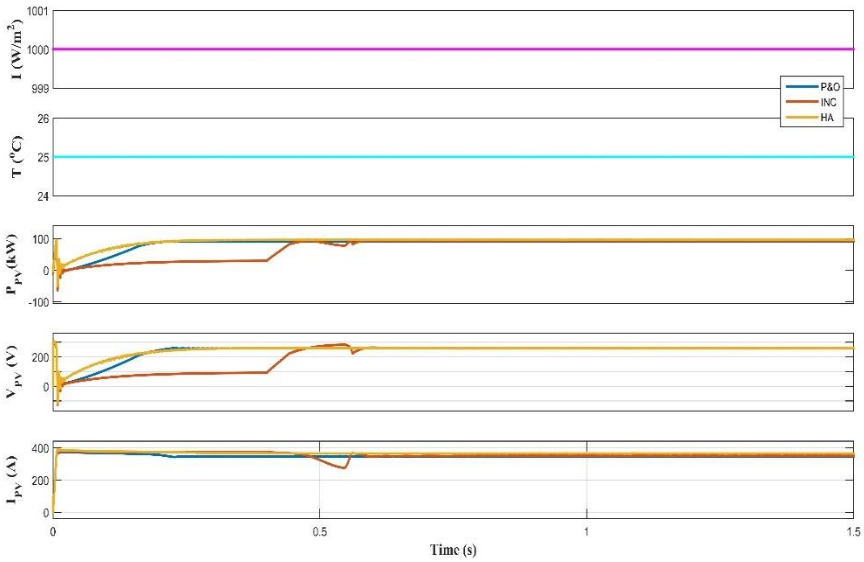

Figure 4 PV output power, terminal voltage, and current

Table 2 Comparison Analysis

Time (s)	Algorithm	Solar radiation (W/M^2)	Solar temperature (°C)	Extracted power (kW)	Load power (kW)
$0 < t_{sim} < 1.5$	P&O	1000	25	83.53	79.55
	IC			71.78	69.15
	Proposed			91.64	88.33

The ultimate purpose of MPPT is to extract as much power as possible from a PV panel; hence, the power collected from the PV panel for each approach must be compared to determine which method extracts the most power. As a result, the simulation waveforms derived from the three provided MPPT approaches are compared in this simulation research. Table 2 clearly shows that the HA-based MPPT method extracts the maximum power at an average of 91.64 kW from 0 to 1.5 s under constant solar insolation (1000 W/m^2) and temperature (25 °C). In contrast, the P&O and IC MPPT techniques extract only 83.53 kW and 71.78 kW, respectively, under constant solar insolation (1000 W/m^2) and temperature (25 °C). Table 2 further shows that under constant solar insolation (1000 W/m^2) and temperature (25 °C), the presented HA-based MPPT approach exports the highest power to the load at an average of 88.33 kW while the P&O and IC MPPT procedures export 79.55 kW and 69.15 kW, respectively. Compared to current MPPT approaches, the presented HA-based MPPT methodology can harvest the most power from the PV panel and provide the maximum power to the loads.

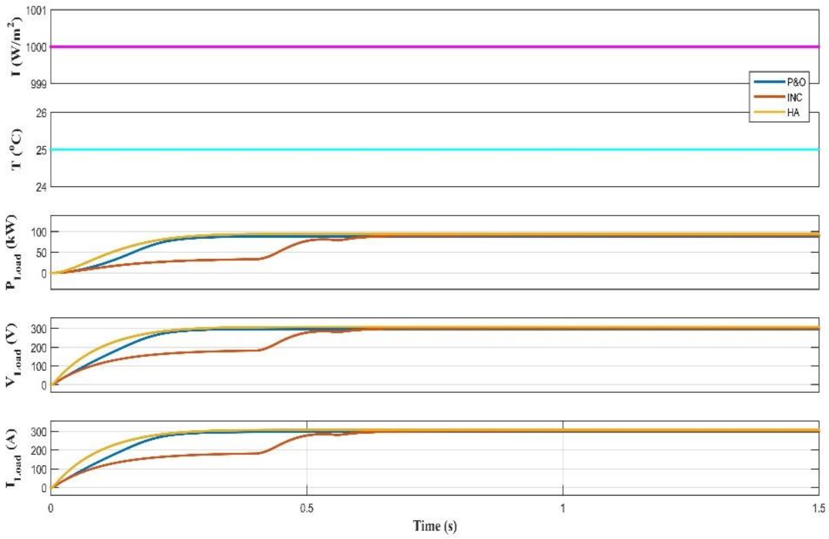

Figure 5 Load power, voltage, and current

5. CONCLUSION

The performance of a novel quick and accurate MPPT controller based on the proposed HA-based MPPT approach has been studied in this article to produce maximum power from the PV array. In PV systems, the HA-based MPPT controller has shown to be a viable solution for MPPT controllers. The hurricane algorithm can avoid the local maximum MPOP caused by nonlinear effects in the PV generating system. According to simulation findings, the suggested HA-based MPPT technology offers tight control and better efficiency with regard to the maximum power output by the PV panel. Furthermore, under constant solar insolation and

temperature, the HA-based MPPT method extracts the highest power at an average of 91.64 kW.

In contrast, the P&O and IC MPPT strategies extract less power than the HA-based MPPT controller. The simulation results also show that the HA-based MPPT approach performs better than current MPPT algorithms such as P&O and IC MPPT controllers. The presented HA-based MPPT controller delivered enhanced power conversion efficiency and improved voltage response characteristics with decreased settling time and overshoot. In the future, the proposed HA-based MPPT controller might be used to monitor global maximum power operating points for wind turbines in a wind energy conversion system.

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